Deaf, Dumb, and Chatting Robots
Enabling Distributed Computation and Fault-Tolerance Among Stigmergic Robot*

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Abstract

We investigate ways for the exchange of information (explicit communication) among deaf and dumb mobile robots scattered in the plane. We introduce the use of movement-signals (analogously to flight signals and bees waggle) as a mean to transfer messages, enabling the use of distributed algorithms among the robots. We propose one-to-one deterministic movement protocols that implement explicit communication.

We first present protocols for synchronous robots. We begin with a very simple coding protocol for two robots. Based on on this protocol, we provide one-to-one communication for any system of $n \geq 2$ robots equipped with observable IDs that agree on a common direction (sense of direction). We then propose two solutions enabling one-to-one communication among anonymous robots. Since the robots are devoid of observable IDs, both protocols build recognition mechanisms using the (weak) capabilities offered to the robots. The first protocol assumes that the robots agree on a common direction and a common handedness (chirality), while the second protocol assumes chirality only. Next, we show how the movements of robots can provide implicit acknowledgments in asynchronous systems. We use this result to design asynchronous one-to-one communication with two robots only. Finally, we combine this solution with the schemes developed in synchronous settings to fit the general case of asynchronous one-to-one communication among any number of robots.

Our protocols enable the use of distributing algorithms based on message exchanges among swarms of Stigmergic robots. Furthermore, they provides robots equipped with means of communication to overcome faults of their communication device.

Keywords: Explicit Communication, Mobile Robot Networks, Stigmergy.

1 Introduction

Research for achieving coordination among teams (or, swarms) of mobile robots is challenging and has a great scientific and practical implications. Swarms of mobile robots are used, and are planned to be even used more, in several critical situations. Swarms provide the ability to measure properties, collect information and act in a given (sometimes dangerous) physical environment. Numerous of potential applications exist for such multi-robot systems, to name only a very few: environmental monitoring, large-scale construction, risky area surrounding or surveillance, and exploration of awkward environments.

In a given environment, the ability for the swarm of robots to succeed in the accomplishment of the assigned task greatly depends on the capabilities the robots have, that is, their moving capacities and sensory organs. Existing technologies allow to consider robots equipped with sensor devices for vision (camera, radar, sonar, laser, etc.) and means of communication (wireless devices). Means of communication are even required to enable classical distributed algorithms and to achieve completion of some tasks like information relay, surveillance, or intelligence activities.

An interesting question is "*What happens if the means of communication are lost or not exist?*" In that case, the robots can observe the location of the robots but cannot communicate with them. Such robots are called *deaf and dumb*. There are numerous realistic scenarios where there is no mean to communicate. Such scenarios are easy to figure out, *e.g.,*

- wireless devices are faulty;

- the robots evolve in zones with blocked wireless communication, *e.g.,* hostile environments where communication are scrambled or forbidden;

- physical constraints prevent to fit out any wireless device on the robots.

The latter can arise for instance when no space is available on the robots or the robots are too small with respect to the size of the wireless device. This would be the case with swarms of nano-robots.

As a matter of fact, the question of solving distributed tasks with swarms of deaf and dumb robots is not a novel one. This question has been extensively carried in different fields of computed science such as artificial intelligence [18], control theory [15, 20, 5], and recently in the distributed computing field [24, 21]. Some of these approaches are inspired of biology studies of the animal behavior, mainly the behavior of social insects [2]. Indeed, these social systems present an intelligent collective behavior although they are composed by simple individuals with extremely limited capabilities. Solutions to problems "naturally" emerge from the self-organization and indirect communication of these individuals. The capacity to communicate using such *indirect communication* (or, *implicit* communication) is referred to as *stigmergy* in the biological literature [17]. There are numerous examples of such indirect communication in nature, for instance from ants and termites communicating using pheromones or from bees, communicating performing waggle dances to find shortest paths between their nest and food sources. The question of whether the waggle of bees is a language or not is even an issue [25].

However, stigmergy allows to make a given task only. Communications are not consider as a task by itself. In other words, the stigmergic phenomenon provides indirect communication, a guidance for a specific work. Even if, sometime stigmergy allows insects to modify their physical environment— this phenomenon is sometime referred to as *sematectonic stigmergy* [11]— stigmergy never provides a communication task by itself. In other words, stigmergy does not allow tasks as chatting, intelligence activities, or sending information which are not related with a given task.

In this paper, we investigate ways for the exchange of information among deaf and dumb mobile robots scattered in the plane. In the sequel, we refer to this task as *explicit communication*— sometime, also referred to as *direct* communication [18]. Explicit communication enables the use of distributed algorithms among the robots. We study the possibility to solve this problem deterministically when robots are communicating only by moving with respect to certain capabilities, namely synchrony, identities, sense of orientation, and chirality.

Contribution. We introduce the use of movement-signals (analogously to flight signals and bees waggle) as a mean to transfer messages between deaf and dumb robots. We propose six one-to-one

deterministic protocols that implement explicit communication.

We first present four protocols for synchronous robots. We begin with a very simple protocol for two robots, showing how high-level information can be coded by simple moves. Based on this protocol, we provide one-to-one communication into any system of $n \geq 2$ robots equipped with observable IDs that agree on a common direction (sense of direction). We then propose two solutions enabling one-to-one communication among anonymous robots. Since the robots are devoid of observable IDs, both protocols build recognition mechanisms using the (weak) capabilities offered to the robots. The third algorithm assumes that the robots have sense of direction and agree on a common handedness (chirality). The fourth protocol assumes chirality only.

In synchronous systems, since every robot is active at each time instant, there is no concern with the receipt of the messages. Indeed, every movement is seen by every robot. As a consequence, no message acknowledgment is required. By contrast, in asynchronous settings, in each computation steps, some robots can be inactive. Thus, few robot movements can be missed out, and as a consequence, some messages. We show how the robot movements can provide implicit acknowledgments in asynchronous settings. We use this result in the design of asynchronous one-to-one communication with two robots only. Finally, we combine this solution with the schemes developed in synchronous settings to fit the general case of asynchronous one-to-one communication among any number of robots.

Note that our protocols—either synchronous or asynchronous—can be easily adapted to implement efficiently one-to-many or one-to-all explicit communication. Also, in the context of robots (explicitely) communicating by means of communication (*e.g.,* wireless), since our protocols allow robots to explicitly communicate even if their communication devices are faulty, in a very real sense, our solution can serve as a communication backup, *i.e.,* it provides *fault-tolerance* by allowing the robots to communicate without means of communication (wireless device).

Related Work.   The issue of handling swarms of robots using deterministic distributed algorithm was first studied in [23, 24]. Beyond supplying formal correctness proofs, the main motivation is to understand the relationship between the capabilities of the robots and the solvability of given tasks. For instance, "*Assuming that the robots agree on a common direction (having a compass), which tasks are they able to deterministically achieve?*", or "*What are the minimal condition to elect a leader deterministically?*"

As a matter of fact, the motivation turns out to be the study of the minimal level of ability the robots are required to have in the accomplishment of some basic cooperative tasks in a deterministic way. Examples of such tasks are specific problems, so that *pattern formation*, *line formation*, *gathering*, *spreading*, and *circle formation*—refer for instance to [24, 12, 6, 21, 3, 22, 7, 4] for this problems,— or more "classical" problems in the field of distributed systems, such that *leader election* [21, 12, 14, 8]. To the best of our knowledge, no previous work addresses the problem of enabling explicit communication in swarms of robots.

Roadmap.   In the next section, we describe the model and the problem considered in this paper. The two following sections (Section 3 and 4) are devoted to synchronous and asynchronous settings, respectively. (Due to the lack of space, proofs are given in the appendix.) Finally, we make some concluding remarks in Section 5. In the same section, extensions and open problems are also discussed.

2 Preliminaries.

In this section, we first define the distributed system considered in this paper. We then state the problem to be solved.

Model. We adopt the model introduced in [23], below referred to as *Semi-Synchronous Model (SSM)*. The distributed system considered in this paper consists of n mobile *robots* (*agents* or *sensors*). Any robot can observe, compute and move with an infinite decimal precision. The robots are equipped with sensors enabling to detect the instantaneous position of the other robots in the plane. Viewed as points in the Euclidean plane, the robots are mobile and autonomous. There is no kind of explicit communication medium.

Each robot r has its own local x-y Cartesian coordinate system with its own unit measure. Given an x-y Cartesian coordinate system, the *handedness* is the way in which the orientation of the y axis (respectively, the x axis) is inferred according to the orientation of the x axis (resp., the y axis). The robots are assumed to have the ability of *chirality*, *i.e.*, the n robots share the same handedness. We consider *non-oblivious* robots, *i.e.*, every robot can remember its previous observations, computations, or motions made in any previous step.

We assume that the system is either *identified* or *anonymous*. In the former case, each robot r is assumed to have a visible (or, observable) identifier denoted id_r such that, for every pair r, r' of distinct robots, $id_r \neq id_{r'}$. In the latter, no robot is assumed to have a visible identified. In this paper, we will also discuss whether the robots agree on the orientation of their y-axis or not. In the former case, the robots are said to have the *sense of direction*. (Note that since the robots have the ability of chirality, when the robots have the sense of direction, they also agree on their x-axis).

Time is represented as an infinite sequence of time instants $t_0, t_1, \ldots, t_j, \ldots$ Let $P(t_j)$ be the set of the positions in the plane occupied by the n robots at time t_j ($j \geq 0$). For every t_j, $P(t_j)$ is called the *configuration* of the distributed system in t_j. $P(t_j)$ expressed in the local coordinate system of any robot r_i is called a *view*. At each time instant t_j ($j \geq 0$), each robot r_i is either *active* or *inactive*. The former means that, during the computation step (t_j, t_{j+1}), using a given algorithm, r_i computes in its local coordinate system a position $p_i(t_{j+1})$ depending only on the system configuration at t_j, and moves towards $p_i(t_{j+1})$—$p_i(t_{j+1})$ can be equal to $p_i(t_j)$, making the location of r_i unchanged. In the latter case, r_i does not perform any local computation and remains at the same position.

The concurrent activation of robots is modeled by the interleaving model in which the robot activations are driven by a *uniform fair scheduler*. In this paper, we discuss whether the system is *synchronous* or *asynchronous*. In the former case, every robot is active at each instant. The latter means that at least one robot is required to be active at each instant.

In every single activation, the distance traveled by any robot r is bounded by σ_r. So, if the destination point computed by r is farther than σ_r, then r moves toward a point of at most σ_r. This distance may be different between two robots.

Problem. *Indirect* communication is the result of the observations of other robots. Using indirect communication, we aim to implement *Direct* communication, that is a purely communicative act, one with the sole purpose of transmitting messages [18]. In this paper, we consider directed communication that aim at a particular receiver. Such communication are said to be *one-to-one*, specified as follows: (*Emission*) If a robot r wants to send a message m to a robot r', then r eventually sends m to r'; (*Receipt*) Every robot eventually receives every message which is meant to it.

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Note that the above specification induces that r is able to address r'. This implies that any protocol solving the above specification have to come up with (1) *Routing* mechanism and (2) *Naming* mechanism, the latter, in this context of anonymous robots.

The specification also induces that the robots are able to communicate explicit messages. So, any one-to-one communication protocol in our model has to be able (3) to code explicit messages with implicit communication, *i.e.,* with (non-ambiguous) movements.

3 One-to-One Communications in Synchronous Settings

It is well-known that in synchronous systems, Emission and Receipt properties are easily verified. Thus, we focus on the three additional properties described above. We first present a solution working for two robots only that shows how explicit information can be easily coded making moves. The second protocol addresses Routing property. Combined with the simple coding mechanism, it provides one-to-one communication into any system of $n \geq 2$ robots equipped with observable IDs and sense of direction. Our third and fourth solutions deal with anonymous networks. Since the robots are devoid of observable IDs, both protocols provide Naming mechanism, *i.e.,* they build recognition mechanisms using the capabilities offered to the robots. The third algorithm assumes that the robots have sense of direction. The last one assumes robots with chirality only (no common sense of direction).

3.1 Coding With Two Robots

Each even step $t_i \mapsto t_{i+1}$ ($i = 2p$, $p \geq 0$) is used by each robot to send a bit in $\{0,1\}$. To send "0" ("1", respectively) to the other robot r', a robot, r, moves on its right (left, resp.) with respect to the direction given by r'—refer to Figure1. To avoid that the robots do not go either too far or near of each other, each odd step $t_{i+1} \mapsto t_{i+2}$ is used by the robots to come back to its first position.

Figure 1: One-to-one communication for 2 synchronous robots.

Note that this simple protocol is *silent* [10] in the following sense: a robot eventually moves if it has some messages to transmit. Also, note that if each robot r knows the maximum distance $\sigma_{r'}$ that the other robot r' can cover in one step, then, the protocol can easily be adapted to reduce the number of moves made by the robots to send bytes. In that case, the total distance $2\sigma_{r'}$ made by r' on its right and its left can be divided by the number of possible bytes send by the robots. Then, r' moves on its right or on its left of a distance corresponding to the byte sent.

3.2 Routing With Identified Robots Having Sense Of Direction

First, for each robot being *a priori* surrounded of several robots, our method requires to include a mechanism avoiding collisions. Next, it must include a technique allowing any robot to send messages

to a specific robot. In order to deal with the collision avoidance, we use the following concept, *Voronoi diagram*, in the design of our method.

Definition 3.1 (Voronoi diagram) *[1] The Voronoi diagram of a set of points $P = \{p_1, p_2, \cdots, p_n\}$ is a subdivision of the plane into n cells, one for each point in P. The cells have the property that a point q belongs to the Voronoi cell of point p_i iff for any other point $p_j \in P$, $dist(q, p_i) < dist(q, p_j)$ where $dist(p, q)$ is the Euclidean distance between p and q. In particular, the strict inequality means that points located on the boundary of the Voronoi diagram do not belong to any Voronoi cell.*

Our protocol requires the two following preprocessing steps—executed at time t_0:

1. Each robot computes the Voronoi Diagram, each Voronoi cell being centered on a robot position—refer to Case (a) in Figure 2, the plain line. Every robot is allowed to move into its Voronoi cell only. This ensures the collision avoidance.

2. For each associated Voronoi cell c_r of robot r, each robot r computes the corresponding *granular* g_r, the largest disc of radius R_r centered on r and enclosed in c_r—Case (a) in Figure 2, the dotted lines. Notice that the radii of different disks might be different. Each granular is sliced into $2n$ slices, *i.e.,* the angle between two adjacent diameters is equal to $\frac{\pi}{n}$. Each diameter is labeled from 0 to $n-1$, the diameter labeled by 0 being aligned on the North, the other are numbered in the natural order following the clockwise direction.

Note that since the robots share a common handedness (chirality), they all agree on the same clockwise direction. Having a common sense of direction, they all agree on the same granular and slice numbering. Once these two preprocessing steps are done, the protocol follows a similar scheme as the case with two robots: when a robot r wants to send a bit to any robot r', to send 0 (resp., 1), r moves inside g_r on the Northern/Eastern/North-Eastern (resp., Southern/Western/South-Western) side on the diameter labeled r'. Next, it comes back to its first position, *i.e.,* the center of g_r.
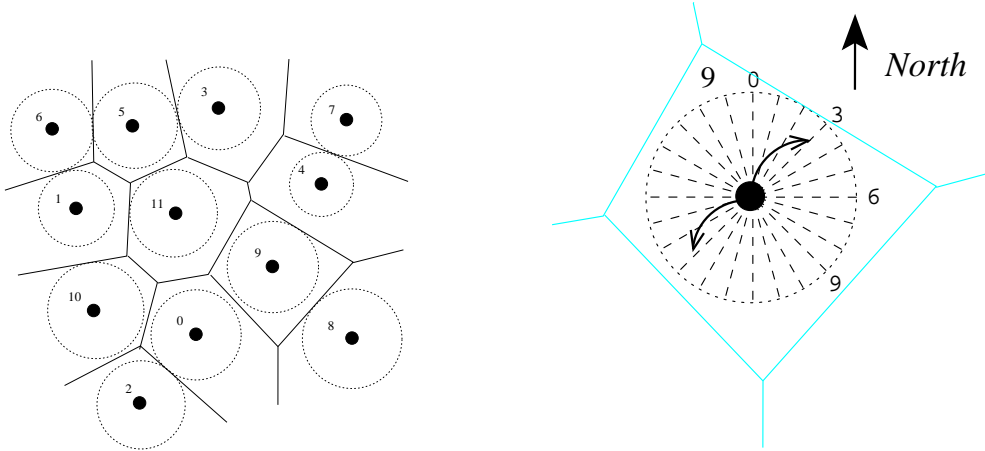
(a) An example showing the system with 12 robots, viewed by each robot after the two preprocessing phases.

(b) Robot 9 sends either "0" or "1" to Robot 3.

Figure 2: One-to-one communication with n identified robots having sense of direction.

3.3 Naming With Anonymous Robots Having Sense Of Direction

It may seem difficult to send a message to a specific robot since no robot has an observable ID. However, it is shown in [12] that if the robots have sense of direction and chirality, then they can agree on a total order over the robots. This is simply obtained as follows: Each robot r labels every observed robot with its local $x - y$ coordinate in the local coordinate system of r. Even if the robots do not agree on their metric system, by sharing the same x- and y-axes, they agree on the same order.

3.4 Naming With Anonymous Robots Without Sense Of Direction

By contrast to the previous case, with the lack of sense of direction, the robots cannot deterministically agree on a common labeling of the cohort. For instance, in Figure 3, the symmetry of the configuration prevent the robots to decide on a common naming, even with the ability of chirality.
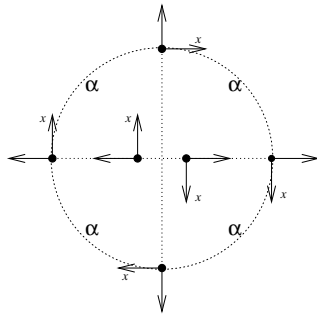

Figure 3: A symmetric example where six robots are scattered in the plane in such a way that for every robot, there is another robot having the same view—the arrows show the local x-y coordinate system of the each robot. They are not able to agree on a common direction nor a common naming.

We now describe our method in the design of a relative (w.r.t. each robot) naming allowing to implement one-to-one communication for anonymous robots having no common sense of direction. We refer to Figure 4 to explain our scheme.

Our method starts (at t_0) with the two preprocessing steps describe above. At the end we have the Voronoi Diagram and the sliced granulars—to avoid useless overload in the figure, the latter are omitted in Figure 4. Then, still at time t_0, each robot r computes the *smallest enclosing circle*, denoted by SEC, of the robot positions. Note that since the robots have the ability of chirality, then they can agree on a common clockwise direction of SEC. Note that SEC is unique and can be computed in linear time [19].

Next, r considers the "*horizon line*", denoted by H_r, as the line passing through itself and $\mathbf{0}$, the center of SEC. Given H_r, r consider each radius of SEC passing through a robot. The robots are numbered in the growing order following the radii in the clockwise direction starting from H_r. When several robots are located on the same radius, they are numbered in the growing order starting from $\mathbf{0}$. Note that this means that r is not necessary labeled by 0 if some robots are located between itself and $\mathbf{0}$ on its radius. An example of this preprocessing phase is shown in Figure 4 for a given robot r.

The method to send messages to a given robot is the same as the previous case. Every robot r slices its granular according to H_r, the diameter corresponding to H_r being labeled by 0 and so on in the clockwise direction. The sending of bit is made following the same scheme as above, the
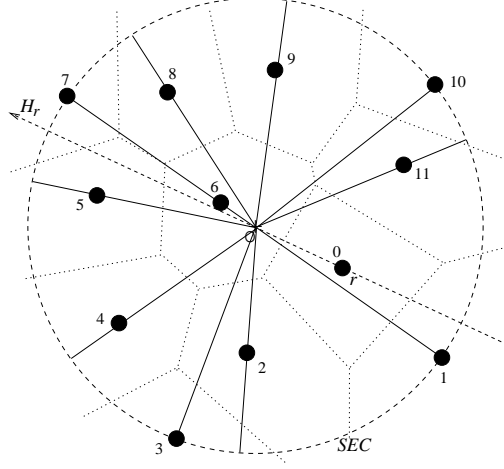
Figure 4: An example showing how the relative naming is built with respect to Robot r.

Northern being given by the direction of H_r and the Eastern following the clockwise direction. Each robot addresses bits according to its relative labeling.

Note first that every robot observes the movements of all the robots. So, every robot is able to know all the messages sent in the system. This could provide fault-tolerance by redundancy, any robot being able to send any message again to its addressee.

Also, note that by construction, the labelling is specific to each robot. However, every robot, r, is able to compute the labelling with respect to each robot of the system. Therefore, for by observing each movement made by any robot r', r is able to know to whom a bit is addressed, and in particular, to itself. Every robot is able to compute the message address, each of them being able to compute the relative naming of all the robots.

4 One-to-One Communications in Asynchronous Settings

In synchronous systems, since every robot is active at each time instant, there is no concern with the receipt of the messages. Indeed, every robot motion is seen by every robot. As a consequence, no message acknowledgment is required. By contrast, in asynchronous settings, only fairness is assumed, *i.e.,* in each computation steps, some robots can remain inactive. So, some robots motions can be lost, and by the way, some messages. Therefore, asynchronous settings require a synchronization mechanism ensuring the acknowledgment of each message sent.

In this section, we mainly focus on the both *Emission* and *Receipt* properties. We first state the two following results—due to the lack of space, the proof of Lemma 4.1 is given in this appendix:

Lemma 4.1 *Let r and r' be two robots. Assume that r always moves in the same direction each time it becomes active. If r observes that the position of r' has changed twice, then r' must have observed that the position of r has changed at least once.*

Proof. By contradiction, assume that at time t_i, r notes that the position of r' has changed twice and r' has not observed that the position of r has changed at least once. Without loss of generality, we assume that t_i is the first time for which r notes that the position of r' has changed

twice. So at time t_i, r knows three distinct positions of r' and $t_i \geq 2$. Let p_j be the last (or the third) position of r' that r has observed, and t_j the first time instant for which p_j is occupied by r'. Obviously, $t_j < t_i$. Now we have two cases to consider :

- **case 1 :** $t_j = t_i - 1$. The fact that r knows three distinct positions of r' implies that r is become active and has moved at least twice between $t = 0$ and $t = t_i - 1$ and, thus at least once between $t = 0$ and $t = t_i - 2$. Consequently, at time $t_j = t_i - 1$, r' would have noted that r's position has changed at least once. Contradiction.

- **case 2 :** $t_j \leq t_i - 2$. We have two cases to consider :

    - **case a :** r' moves at least once between $t_j + 1$ and $t_i - 1$. In that case, r notes that the position of r' has changed twice before time t_i : that contradicts the fact that t_i is the first time for which r notes that the position of r' has changed twice.

    - **case b :** r' does not move between $t_j + 1$ and $t_i - 1$. As mentioned above, the fact that r knows three distinct positions of r' implies that r is become active and has moved at least twice between $t = 0$ and $t = t_i - 1$. However, r' does not move between $t_j + 1$ and $t_i - 1$. Hence, r has moved at least twice between $t = 0$ and $t = t_j$ and, thus at least once between $t = 0$ and $t = t_j - 1$. So, at time t_j r' would have noted that r's position has changed at least once. Contradiction.

$\square$

Corollary 4.2 *Let r and r' be two robots. Assume that r always moves in the same direction on a line l as soon as it becomes active. If r observes that the position of r' has changed twice, then r' knows the line l and the direction toward which r moved.*

4.1   One-to-One Communications With Two Asynchronous Robots

Both robots follow the same scheme, in the sequel referred to as Protocol $\mathtt{Async}_2$. Each time a robot, let us say r, becomes active, it moves in the opposite direction of the other robot, r'. Let us call this direction the $North_r$. Robot r behaves like this while it has nothing to send to r'. As soon as r observes that the position of r' changed twice, by Corollary 4.2, r is guaranteed that r' knows the line H and the direction on which r has moved. Let us call the line H the *horizon line*. Note that since the two robots follow the same behavior, H is common to both of them and their respective North are oriented in the opposite direction.

From this point on, r can start to send messages to r'. When r wants to send a bit "0" ("1", respectively) to r', r moves along a line perpendicular to on the Est side (West side, resp.) of H with respect to $North_r$. It then move in the same direction each time it becomes active until it observes that the position of r' has changed twice. At this moment on, from Lemma 4.1, r knows that r' has seen it in its Est side. Then, r comes back on H. Once r is located on H, it starts to move again toward the $North_r$ direction until it observes that r' has moved twice. In this way, if Robot r wants to communicate another bit (following the same scheme), it is allowed to move on its East or West side again. So, the new bit and the previous bit are well distinguished by Robot r' even if they have the same value. An example of our scheme is shown in Figure 5.

Note that by Lemma 4.1, Protocol $\mathtt{Async}_2$ ensures the *Receipt* property provided the following condition: r observed that the position of r' changed twice before any direction change. We now show that Protocol $\mathtt{Async}_2$ ensures this condition.

Figure 5: Asynchronous one-to-one communication for 2 robots. Robot r sends "001...", Robot r' sends "0...".

Remark 4.3 *If any robot becomes active, then it moves.*

Lemma 4.4 *Let r and r' be two robots. In every execution of Protocol $\texttt{Async}_2$, r observes that the position of r' changes infinitely often.*

Proof. Assume by contradiction that, there exists some executions of Protocol $\texttt{Async}_2$ such that, eventually, r observes that that position of r' remains unchanged. Consider the suffix of such an execution where r observes that the position of r' remains unchanged. Assume that r' is eventually motionless. By fairness and Remark 4.3, this case is impossible. So, r' moves infinitely often. Thus, each time that r observes r', r' is at the same position. There are two cases to consider:

1. Robot r' eventually sends no bit. In that case, by executing Protocol $\texttt{Async}_2$, r' moves infinitely often in the same direction on H. Which contradicts that each time that r observes r', r' at the same position.

2. Robot r' sends bits infinitely often. Since r' is at the same position each time r observes it, r' goes in a direction and comes back at the same position infinitely often. So, from Protocol $\texttt{Async}_2$, r' observed that the position of r changed twice infinitely often (each time r' changes its direction). By Lemma 4.1, each time r' observes that the position changed twice, r observes that the position of r' has changed at least once. A contradiction.

$\square$

Lemmas 4.1 and 4.4 ensures that Protocol $\texttt{Async}_2$ ensures the *Receipt* property. Furthermore, Lemma 4.4 ensures that no robot is starved sending a bit (*i.e.,* it can change its direction infinitely often). So, Property *Emission* is guaranteed by Protocol $\texttt{Async}_2$. That leads to the following theorem:

Theorem 4.5 *Protocol $\texttt{Async}_2$ implements one-to-one explicit communication for two robots.*

However, this scheme has the drawback of making the two robots moving away infinitely often of each other. To deal with this drawback, the two robots can alternate their direction on H each time they send a new bit. Lemmas 4.1 and 4.4 ensure that no bit would be missed. However, with this protocol, the robots can collide together. To avoid that the robots neither collide, they can

divide the covered distance by $x > 1$ in each move. This introduces another drawback: the robots are required to be able to move an infinitesimally small distance. This is also the main drawback of the protocol of any number of robots in the next subsection.

4.2 One-to-One Communication For Any Number Of Anonymous Asynchronous Robots

We now combine the previous method with the one developed in Section 3. In the following, we describe our method assuming anonymous robots , devoid of sense of direction, *i.e.,* the weakest assumptions made in Section 3. Obviously, our method is also compatible with extra assumptions, namely IDs or sense of direction.

   We assume that the robots knows $P(t_0)$, *i.e.,* the positions of the robots are known by every robot in t_0 or all the robots are awake in t_0. Using $P(t_0)$, when a robot wakes for the time (possibly after t_0), it computes all the preprocessing steps, including the computation of SEC. The only difference is that the granular is sliced in $n + 1$ slices—instead of n slices as in the synchronous case. Consider that the extra slice, corresponding to H_r, the diameter being on radius of SEC passing through r) is not assigned to a particular robot. Let us call this slice κ. In our method, κ plays the role of the horizon line H as for the case with two robots—refer to Figure 6. That is, each robot moves on its respective κ to indicate that it has no bit to transmit.
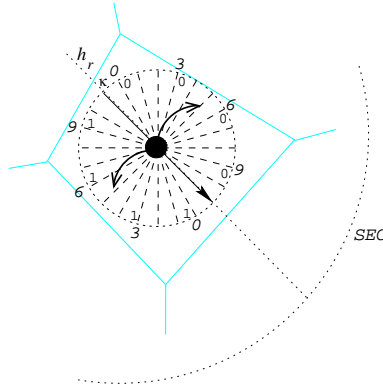

Figure 6: An example showing how the granular is sliced with respect to r.

   Thus, for every robot r, Protocol $\texttt{Async}_n$ works as follows:

1. If r wants to send a bit to a robot r', then if r is not at the center of its granular then it comes back on this latter one. Then, r moves on the Northern/Estern/North-Estern (resp., Southern/Western/South-Western) side on the diameter labelled with r'. It then moves in the same direction on the diameter labelled r' each time it becomes active. To make sure that all the robots observed its movement, r moves in the same direction until it observes that the position of every robot changed twice. Next, r comes back to the center of its granular (*i.e.,* its initial position in $P(t_0)$ by moving along the same slice. Finally, it moves in the same direction on κ avoiding to reach the border of its granular before it observes that the position of every robot changed twice. In this way, it is now allowed to send a new bit by following the same scheme and we are sure that the new bit and the previous bit are well distinguished by Robot r' even if they have the same value.

2. If r does not want to send a bit, then while r does not want to send any bit, it moves in the same direction on κ avoiding to reach the border of its granular before it observes that the position of every robot changed twice. When the latter occurs, it moves on the opposite direction, and so on. If eventually, r wants to send a bit, then it comes back toward the center following the same rule as the first case.

Note that in both case, while a robot is moving toward a direction (on a slice), it must avoid to reach either the border or the center of the granular. In order to implement this constraint, it is required the robots divide the covered distance by $x > 1$ in each move. Also, as for the synchronous case, every robot is able to read every message sent by any robot r to any robot r', enabling a kind of redundancy.

By applying the same reasoning as in Subsection 4.1 for every pair of robots, we can claim:

Theorem 4.6 *Protocol* $\mathtt{Async}_n$ *implements one-to-one explicit communication for two robots.*

5 Concluding Remarks, Extensions, and Open Problems

In this work we proposed (deterministic) movement protocols that implement explicit communication, and therefore allow the application of (existing) distributed algorithms; distributing algorithms that use message exchanges. Movements-signals are introduced as a mean to transfer messages between deaf and dumb robots. The movement protocols can serve as a backup to other means of (e.g., wireless) communication.

In this paper we first presented protocols for synchronous robots. Some of them assume that the robots are equipped with observable IDs and that the robots agree on a common direction. We also proposed protocols enabling one-to-one communication among anonymous robots by building recognition mechanisms assuming the robots share a common handedness only. Note that the robots may decide to flock in a certain direction, subtracting the agreed upon global flocking movement in order to preserve the relative movements used for communication.

We have adapted the protocols developed in synchronous settings to fit the general case of asynchronous one-to-one communication among any number of robots.

Next, we list several notable extensions and open problems.

Silent, Finite Movements and Discrete Computation. We call the ability for a communication protocol to be *silent* when a robot eventually moves if it has some message to transmit. Note that this desirable property would help to save energy resources of the robots. The protocols proposed with synchronous settings (Section 3) are clearly silent. Our asynchronous solutions are not silent (Remark 4.3). The question of whether the design of silent asynchronous algorithms is possible or not is open. A related issue concerns the *distance (eventually) covered* by the robots. In this paper, we could not overcome either infinite growing distance or infinitely decreasing distance. As a matter of fact, we believe that the fact that an asynchronous robot that sequentially observes another robot at the same place, cannot determine whether the robot moved and returned to the same position or did not move at all, implies an impossibility for a communication by a finite number of moves.

Computations with an *infinite decimal precision* is different and, in a way, weaker assumption than infinitely small movements. Indeed, one can assume infinite decimal precision with the "reasonable" assumption of finite movements, *i.e.*, with a *minimal* and *maximal* distance covered in one atomic

step, or even step over a grid. In this paper, we assumed a maximal covered distance (σ_r), but not a minimal covered distance. This would be the case by assuming that the plane is either a grid or a hexagonal pavement [16]. For instance, with such assumption, the robots could be prone to make computation errors due to round off, and, therefore, face a situation where robots are not able to identify all of possible $2n$ directions obtained by slices inside of disks and are limited to recognize only a certain number of directions. This case could be solved by avoiding the use of $2n$ slices of granular by transmitting the index of the robot to whom the message intended following the message itself. For this we would need only $k + 1$, $1 \leq k < 2n$ segments (or $2k + 1$ slices). In particular, we would use one segment for message transmission (as in the case of two robots); using the other k segments the robot who wants to transmit a message allows to transmit the index of the robot to whom the message is designated. Definitely, such index can be represented by $\frac{\log n}{\log k} = \log_k n$ symbols. Notice, this strategy would slow down the algorithm and increase the number of steps required to transmit a message. More precisely, the number of steps required in this method to identify the designated robot is $\log_k n$. For example, by taking $O(\log n)$ slices instead of $O(n)$, the number of steps to transmit a message would increase by $O(\frac{\log n}{\log \log n})$.

Partial synchrony. In the continuity of the above discussion, an other important feature in the field of mobile robots is the weakness/strength of the model. For instance, in this paper, we used the semi-synchronous model (SSM). It would be interesting to achieve solutions by *relaxing synchrony* among the robots to achieve solutions into a fully asynchronous model (*e.g.,* , CORDA [21]).

Visibility. Another issue would the *visibility capability* of the robots [13]. For instance, the following question could be investigated: "Can one-to-one communication be achieved by a team of robots with limited visibility?" With the same approach, the problem of explicit communication could be addressed assuming that the amount of *memory* the robots are equipped with is bounded.

Stabilization. *Stabilization* [9] would be a very desirable property to enable. It seems that, in our case, stabilization can be achieved in the synchronous case by carefully adapting the protocols proposed in Section 3; say by assuming a global clock (using GPS input) returning to the initial location and (re)computing the prepossessing phase every round timestamp. The self-stabilization property for the asynchronous case requires further study.

References

[1] F Aurenhammer. Voronoi diagrams- a survey of a fundamental geometric data structure. *ACM Comput. Surv.*, 23(3):345–405, 1991.

[2] R. Beckers, O.E. Holland, and J.L. Deneubourg. From local actions to global tasks: Stigmergy and collective robotics. *Artificial Life, 4th Int. Worksh. on the Synth. and Simul. of Living Sys.*, 4:173–202, 1994.

[3] M Cieliebak, P Flocchini, G Prencipe, and N Santoro. Solving the robots gathering problem. In *Proceedings of the 30th International Colloquium on Automata, Languages and Programming (ICALP 2003)*, pages 1181–1196, 2003.

[4] R Cohen and D Peleg. Local spreading algorithms for autonomous robot systems. *Theor. Comput. Sci.*, 399(1-2):71–82, 2008.

[5] C.R.Kube. Task modelling in collective robotics. *Auton. Robots*, 4(1):53–72, 1997.

[6] X Defago and A Konagaya. Circle formation for oblivious anonymous mobile robots with no common sense of orientation. In *2nd ACM International Annual Workshop on Principles of Mobile Computing (POMC 2002)*, pages 97–104, 2002.

[7] Y Dieudonné, O Labbani-Igbida, and F Petit. Circle formation of weak mobile robots. *ACM Transactions on Autonomous and Adaptive Systems*, 3(4), 2008.

[8] Y Dieudonné and F Petit. Deterministic leader election in anonymous sensor networks without common coodinated system. In *11th International Conference On Principles of Distributed Systems (OPODIS 2007)*, volume 4878 of *Lecture Notes in Computer Science, Springer*, pages 132–142, 2007.

[9] S. Dolev. *Self-Stabilization*. The MIT Press, 2000.

[10] S. Dolev, MG Gouda, and M Schneider. Memory requirements for silent stabilization. In *PODC96 Proceedings of the 15th Annual ACM Symposium on Principles of Distributed Computing*, pages 27–34, 1996.

[11] E.O.Wilson. *Sociobiology*. Belknap Press of Harward University Press, 1975.

[12] P Flocchini, G Prencipe, N Santoro, and P Widmayer. Hard tasks for weak robots: The role of common knowledge in pattern formation by autonomous mobile robots. In *10th Annual International Symposium on Algorithms and Computation (ISAAC 99)*, pages 93–102, 1999.

[13] P Flocchini, G Prencipe, N Santoro, and P Widmayer. Gathering of autonomous mobile robots with limited visibility. In *STACS 2001*, pages 247–258, 2001.

[14] P Flocchini, G Prencipe, N Santoro, and P Widmayer. Pattern formation by autonomous robots without chirality. In *VIII International Colloquium on Structural Information and Communication Complexity (SIROCCO 2001)*, pages 147–162, 2001.

[15] T. Fukuda and S. Nakagawa. Approach to the dynamically reconfigurable robotic sytem. *Journal of Intelligent and Robotic System*, 1:55–72, 1988.

[16] N Gordon, I A. Wagner., and A M. Brucks. Discrete bee dance algorithms for pattern formation on a grid. In *IAT '03: Proceedings of the IEEE/WIC International Conference on Intelligent Agent Technology*, pages 545–549. IEEE Computer Society, 2003.

[17] P-P Grassé. La reconstruction du nid et les coordinations inter-individuelles chez bellicositermes natalensis et cubitermes sp. la theorie de la stigmergie: Essai dinterpretation des termites constructeurs. *Insectes Sociaux*, 6:41–83, 1959.

[18] M.J. Matarić. Issues and approaches in the design of collective autonomous agents. *Robotics and Autonomous Systems*, 16(2-4):321–331, 1995.

[19] N Megiddo. Linear-time algorithms for linear programming in $\smallsetminus^3$ and related problems. *SIAM Journal on Computing*, 12(4):759–776, 1983.

[20] F.R. Noreils. An architecture for cooperative and autonomous mobile robots. In *IEEE International Conference on Robotics and Automation*, pages 2703–2710, 1992.

[21] G Prencipe. *Distributed Coordination of a Set of Autonomous Mobile Robots.* PhD thesis, Dipartimento di Informatica, University of Pisa, 2002.

[22] G Prencipe and N Santoro. Distributed algorithms for autonomous mobile robots. In *The 2006 IFIP International Conference on Embedded And Ubiquitous Computing (EUC 2006)*, 2006.

[23] I Suzuki and M Yamashita. Agreement on a common x-y coordinate system by a group of mobile robots. *Intelligent Robots: Sensing, Modeling and Planning*, pages 305–321, 1996.

[24] I Suzuki and M Yamashita. Distributed anonymous mobile robots - formation of geometric patterns. *SIAM Journal of Computing*, 28(4):1347–1363, 1999.

[25] P.H Wenner and A.M Wells. *Anatomy of a Controversy: the Question of a "Language" Among Bees.* Columbia University Press, New-York, 1990.